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Review Article

Motor nerve transfers for reconstruction of traumatic upper extremity nerve injuries – a scoping review☆,☆☆

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ABSTRACT

Peripheral nerve injuries to the radial, median, and ulnar nerves have been traditionally treated via direct repair or interposition nerve grafts. Late presentation or failed functional restoration may be salvaged with tendons transfers. Nerve transfers may be deployed either as an adjunct to a proximal reconstruction or as a primary reconstructive strategy, and these techniques are being increasingly adopted as the published evidence matures. The advantages of nerve transfers include shorter reinnervation distances, restoration of original muscle action, and maintenance of independent muscle function. Tendon transfers are reliable, not dependent on time, and the functional use of the limb is often achieved quickly,. Hybrid combinations that combine nerve and tendon transfers can also be used to maximize the recovery potential. This scoping review aimed to provide an overview of nerve transfer possibilities after peripheral nerve injuries and guide man-

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agement decisions for clinicians treating patients with upper limb paralysis from peripheral nerve injuries.

Introduction

Traumatic upper extremity nerve injuries are common. In a United States database, 2.6% patients with upper extremity trauma were diagnosed with a peripheral nerve injury (PNI).[1] Historically, tendon transfers have been the mainstay treatment for persistent paralysis after PNI. Nerve transfers (NTs) are incorporated in treatment algorithms when complete recovery of a PNI is not expected.[2]

Denervation of a muscle after PNI leads to muscle fiber degeneration. A completely denervated muscle needs to be reinnervated within a critical time frame to prevent irreversible muscle fiber loss.[3] The reinnervation timeframe is widely regarded as being approximately 1 year. Muscles that are far distal to the site of nerve repair may fail to be reinnervated owing to inadequate axonal regeneration within the critical timescale. Early NT may be offered as a potential treatment to prevent muscle function loss due to critical muscle fiber degeneration. An expendable donor nerve, close to the muscle to be reinnervated, is transferred as close to the recipient nerve entry point into the muscle as possible.[4,5] Numerous options for NT in the upper extremity have been described,[6-8] especially when the injury is isolated to one main nerve trunk, leaving others available for nerve or fascicle transfer. Knowledge of the available transfers techniques and the expected outcomes can help surgeons and patients decide on the optimal treatment after a PNI that provides satisfactory recovery.[5]

For this scoping review, we focused on motor NTs in the upper limb for injuries to the radial, median, and ulnar nerves where tendon transfers are well established, but NT options are still new. In most cases, NTs are offered only in PNI centers. We determined the kinds of motor NTs described in the literature for these injuries, reported the outcomes of these NTs, and discussed our experience. We have not included the management of axillary or musculocutaneous nerve injuries, as these have well established NT options that are widely documented in the literature.

Methods

Medline, PubMed, Cochrane, and CINAHL databases were searched for published articles on NTs used to reconstruct traumatic peripheral nerve injuries of the upper extremity, namely the radial, median, and ulnar nerve injuries. The following search terms were used: radial nerve, median nerve, ulnar nerve, PNI, and NTs. We searched the references of included studies for other relevant studies. Our search yielded 444 articles, among which a total of 165 abstracts were screened. Articles on tendon transfers, transfers for axillary and musculocutaneous nerve injuries and amputations were excluded. Only articles published in the English language were included. Articles with combined etiology were included if individual data were provided for traumatic peripheral nerve injuries and transfers.

As this is a scoping review, no formal quality appraisal was performed, and no study registration was required. We included one randomized controlled trial.[9] A data-charting form was jointly developed by the three authors to determine which variables to extract. Then, all the authors independently charted the data, discussed the results, and continuously updated the data-charting form in an iterative process. This was repeated for each of the 3 reviewed nerves and included as appendices. We abstracted data on population demographics, level of injury, time to surgery, procedure undertaken, length of follow-up, and clinical outcome. Most studies on motor NTs included muscle strength graded according to the British Medical Research Council Manual Muscle Testing scale (MRC).

The final analysis included 13 articles on radial nerve injury (Table 1), 9 on median nerve injury (Table 2), and 19 on ulnar nerve injury (Table 3).

Table 1
Articles reporting outcomes from motor nerve transfers for high radial nerve injuries.

No	Author	Year	Patients	Age (y) (Avg)	Level of injury: Forearm	Elbow	Arm	Time to surgery (Months)	Procedure	Follow up (months)	Outcome (M3/4)	comments
1	*Lurje*	*1948*	2	21			2	15	MCN to radial nerve	12	Wrist extension (M3), Finger (M0) 2/2	
2	*Lowe*	*2002*	2	39				2	FDS to ECRB and PL to PIN		Wrist and finger extension M4 2/2	
3	*Mackinnon*	*2007*	1	32			1	7	FDS to ECRB and FCR/ PL to PIN	10	1 (100%)	
4	*Ray*	*2010*	19	41			19	6	FDS and PL/FCR to ECRB and PIN		Wrist 18/19 M4<, Finger 12/19 M4, 2/19 M3, 5/19 poor	
5	*Plate 2013*	*2013*	1	26			1	11	PB to PIN and Sural graft posterior cord	3 years	Wrist and fingers M4	
6	*Garcia-Lopez*	*2013*	6	25			6	5	PT to ECRL and FCR to PIN	20	Wrist M4 6/6 and Finger 4/M4 and 2/M3	
7	*Pet*	*2016*	1	36			1	3	FCR to PIN and FDS to ECRB and PT to ECRB tendon transfer	8	NR	
8	*Larson*	*2019*	1	12			1	1	FCR + PL to PIN and FDS to ECRB and PT to ECRB tendon transfer	4.5 years	Wrist and fingers M4<	
9	*Bertelli*	*2019*	5	30			5	10	DPT to ECRB	25	Wrist M4	
10	*Bertelli*	*2019*	14	28			14	6	PQ to ECRB and FCR to PIN	26	Wrist 13 M4 and 1 M3 - Finger 8/14 M4 4/14 M3 and 2 failure	
11	*Bertelli*	*2019*	5	29			5	9	FCR to PIN and PT to ECRB and DAIN to DBPIN	19	NR	
12	*Tian*	*2022*	5	33			5	9	PT to ECRB and FCR to PIN	10	Wrist 5/5 M4 and fingers 5/5 M4	
13	*Patterson*	*2022*	16	32			16	28	FCR to PIN and FDS to ECRB and PT to ECRB tendon transfer	17	Wrist 11/13 M4 Finger extension 7/11 M4	
Total/Average												

MCN: Musculocutaneous, **FDS**: Flexor digitorum superficialis, **ECRB:** Extensor carpi radialis brevis, **PL**: Palmaris longus, **PIN**: Posterior interosseous nerve, **FCR:** Flexor carpi radialis. **PT**: Pronator teres, **DPT**: **PQ:** Pronator quadratus

Table 2
Articles reporting outcomes from motor nerve transfers for high median nerve injuries.

No	Author	Year	Patients	Age (y) (Avg)	Level of injury: Forearm	Level of injury: Elbow	Level of injury: Arm	Time to surgery (Months)	Procedure	Follow up (months)	Outcome (M3/4)	Comments
1	*Schultz*	*1972*	1	22	1			2	Third lumbrical branch to thenar branch	3	M3/M4 ?	unclear M3 or M4
2	*Hsaio*	*2008*	1	65			1	18	ECRB to PT and SB to AIN	18	M4	
3	*Ray*	*2012*	4	35			4	3	BraB to AIN	26	3/4 M4; 1/4 M3	
5	*Bertelli*	*2014*	4	28			4	5	ECRB to AIN	13	4/4 M4	
6	*Bertelli*	*2017*	5	32		2	3	5	ECRB to AIN + ADQMB to TBMN	13	5/5 M4	75% grasp and pinch strength
7	*Ozcelik*	*2020*	2	30			2	NR	FPIU to TBMN	6	2/2 M3/M4	unclear M3 or M4
8	*Salomao*	*2020*	1	29			1	16	ECRB to AIN	24	1 M4	
9	*Medina*	*2022*	1	18			1	5 d	ECRB to AIN	24	M3/M4	unclear M3 or M4
Total/Average												

ECRB: Extensor carpi radialis brevis, **PB:** Palmaris brevis brevis, **SB:** Supinator branch, **AIN:** Anterior interosseous nerve
BraB: Brachialis, **ADQMB:** Adductor digiti quenti motor branch, **TBMN:** Thenar branch motor nerve

Table 3
Articles reporting outcomes from nerve transfers for high ulnar nerve injuries.

No	Author	Year	Patients	Age (y)	Level of injury			Time to surgery	Procedure	Follow -up	Outcome (M3/4)	Comments
				(Avg)	Forearm	Elbow	Arm	(Months)		(months)	(Ulnar intrinsics)	
1	*Battiston*	*1999*	7	32		6	1	4	AIN + PCBMN ETE	30	5/7 M4; 1/7 M5	
2	*Novak*	*2002*	8	38			8	3	AIN	18	NR	Pinch and grip improved 8/8
3	*Haase*	*2002*	2	48			2	0.75	AIN	12	NR	Return hand funciton 2/2
4	*Sherif*	*2010*	2	36	1		1	4	Double ETS Bridge graft	9	1/2 M3; 1/1 M4	
5	*Flores*	*2011*	5	22		1	4	7.4	AIN + TCPDN ETC	20	2/5 M3; 3/5 M4	
6	*Chan*	*2012*	1	44	1			1.5	AIN + Graft	36	1/1 M4	
7	*Delclaux*	*2014*	1	35			1	18	AIN + PIN	18	M3	
8	*Flores*	*2015*	15	28		3	12	7.1	AIN + TCPDN ETS	24.3	5/15 M3; 7/15 M4	
9	*Semaya*	*2015*	4	24		1	3	3.3	AIN + PCBMN ETE	22	NR	Good hand function 3/4
10	*Baltzer*	*2016*	6	35	5	1	1	5.9	AIN SETS	13.5	NR	Improvement intrinsic function
11	*Gesslbauer*	*2016*	3	34	3			10	Double ETS Bridge graft	72	1/3 M3; 2/3 M4	
12	*Sallam*	*2017*	24	33		16	8	9.4	AIN + TCPDN ETE	28.6	12/24 M3; 8/24	
13	*Bertelli*	*2018*	3	37	1	1	1	20	OPB-TDDUN	15.3	NR	Improvement pinch
14	*Isaacs*	*2019*	1	49		1		5	AIN	12	NR	Intrinsic reinnervation
15	*Koriem*	2020	11	35	6		9	1	AIN-ETS	18	1/11 M3; 9/11 M4	
16	*Nyman*	2021	2	22	2			12	AIN-ETS	24	NR	Instrinsic reinnervation
17	*Arami*	2021	11	33	2		9	5	AIN-ETE	19	NR	No clawing correction
18	*Chen*	2021	13	38	8	2	3	9	AIN-ETS	12	NR	Grip and pinch improvement
19	George	2021	16	39	3	8	5	1	AIN-ETE + ETS	17	7/16; 6/16 M4	
Total/Average												

AIN: Anterior interosseous nerve, **PCBMN:** Palmar cutaneous branch of the median nerve, **ETE:** End-to-end, **ETS:** End-to-side, **TCPDN:** Third common palmar digital nerve, **SETS:** Supercharge end-to-side, **PIN:** Posterior interosseuous nerve,
DASH: Disability of the Arm, Shoulder and Hand, **OPB**: Opponens pollicis branch, **TDDUN:** Terminal division of deep branch of ulnar nerve, **MRC (M):** Medical Research Council

Results

Radial nerve

In 1948, Lurje described the transfer of the musculocutaneous nerve—distal to the branches to biceps—to the distal radial nerve in 2 patients with large radial nerve defects. Some restoration of wrist extension was achieved, but there was no thumb or finger extension 15 months after the transfer.[10] In 2002, the concept was revived when a certain degree of wrist and independent finger extension was achieved in 2 patients after the transfer of the flexor digitorum superficialis (FDS) branch to extensor carpi radialis brevis (ECRB) and a palmaris longus (PL) branch to the posterior interosseous nerve (PIN).[11] Later, the same group reported a single case with recovered wrist and finger extension (MRC 4/5) 18 months after transferring the flexor carpi radialis (FCR)/PL branch to the PIN and a redundant FDS branch to ECRB.[12] Donor deficits were minor because multiple nerve branches innervate the FDS muscle, and PL is deemed expendable.

Another group reported the transfer of a single pronator teres (PT) branch to extensor carpi radialis longus (ECRL) and the FCR motor nerve to the PIN in 6 patients. Twenty months after surgery, the patients experienced M3 and M4 strength in the radial nerve innervated muscles.[13] They hypothesized that this set of NTs possibly overcame the problem related to the FDS to ECRB transfer, whereby wrist extension was achieved using finger flexion; this complicated reaching out to grasp objects with an extended wrist. The authors noted that any early radial deviation because of ECRL activity was balanced out as ECU began to function through the FCR to PIN transfer. In most of the studies in Table 1, MRC grade for wrist extension was superior to that for finger extension. The three most recent studies compared tendon transfers to NTs for radial nerve palsy and found that NT had superior outcomes in terms of MRC grades, range of motion, and improved grip strength.[14-16] Notably, a PQ (anterior interosseus nerve [AIN]) to ECRB transfer achieved a greater range of motion, without radial deviation and better grasp strength than the traditional PT to ECRB tendon transfer.[14]

Median and anterior interosseus nerve

The expected function loss after a high median nerve injury remains debatable.[17] The median nerve innervates both pronator muscles. However, at 21 weeks after injury, mean pronation was 52°, and 10 out of 11 people had MRC grade 4 pronation strength, possibly owing to compensation from other muscle actions.[18] This may explain why the literature review yielded only two reports on neurotization of the PT including a single case of ECRB branch transfer[19] and 2 cases of FDS NT.[18] As the recovery of pronation appears to be expected, assigning success to the NT would be difficult.

In one study, all 11 patients had MRC grade 5 wrist flexion after high median nerve injury, likely due to FCU compensation, without ulnar deviation (possibly due to learned abductor pollicis longus compensation).[18] However, the long finger proximal interphalangeal and distal interphalangeal flexion was preserved, probably due to partial ulnar innervation, but flexion at the index finger proximal interphalangeal and distal interphalangeal and flexion at the interphalangeal joint of the thumb were lost. NT to the AIN might mitigate this functional loss. Three NTs to the AIN have been reported: (1) brachialis[20]; (2) supinator (Table 2)[19]; and (3) ECRB.[21] The number of cases in these reports varied from 1 to 4 and the achieved FPL and FDS MRC grade was 3 or 4.

Noticeable loss of thumb function appeared to be less frequent, probably due to dual ulnar innervation of some portions of the thenar muscles. In one series, only 14% (21/147) chose to undergo opponensplasty after median nerve injury.[22] Others reported 36% (8/22) of patients losing thumb pronation.[23] The intrinsic thumb functional loss, which can be disabling, can be treated with a NT into the thenar branch. Various donor nerves have been described, including the third lumbrical (n=1), the first palmar interosseus branch of the ulnar nerve, and abductor digit quinti (ADQ) transfer (n=5).[24] The ADQ transfer achieved 75% contra-lateral grip and pinch strength without losing small finger abduction.[25]

Ulnar nerve

Hand weakness is the most common functional deficit after ulnar nerve injury.[26] One study reported 85% (61/72) good or satisfactory motor recovery at a mean of 18 months (SD 23) after primary repair of partial or complete forearm ulnar nerve injuries. Two case series reported that 10% (2/20, minimum 20 months after surgery) and 57% (16/28, minimum 24 months after surgery) of patients achieved motor recovery (MRC grade 3/4) after ulnar nerve grafting proximal to the elbow (Table 3).[27,28] Both comparative case series found better recovery(MRC grade 3/4) after NT in 80% [12/15] and 83% [20/24]). Most studies reported transferring the AIN, by harvesting it as it enters the pronator quadratus, to the motor fascicle group of the ulnar nerve proximal to the wrist.

Among the patients studied in our review, 88% (96/136) achieved MRC grade 3 or 4 after AIN transfer. Interestingly, one case series found that clawing persisted in all patients at (n=11) 19 months (range, 12 to 30 months) after end-to-end AIN transfer.[29] Several studies reported performing a reverse end-to-side transfer of the AIN to the ulnar nerve after proximal ulnar nerve transection.[9,30-32] The single randomized controlled trial included in this review compared primary ulnar nerve repair (control; n=10), with repair and reverse end-to-side transfer (intervention; n=11). At 18 months after surgery, they reported MRC grade 5 in 10 (91%) participants in the intervention group and only in 4 (40%) from the control group.[9] A single case report of an absent pronator quadratus, precluding this transfer was also noted.[33] Moreover, transfer of the distal stump of the transected ulnar nerve using an end-to-side technique to the intact median nerve at the wrist failed to restore function (3 patients had no recovery and the other 5 were lost to follow-up).[34] There were 5 reported cases of bridge grafts from the median nerve to the ulnar nerve. One study involving 3 patients reported MRC grade 4 in all intrinsic muscles after bridge grafting from the recurrent branch of the median to the ulnar nerve.[35] The other 2 cases involved sharp forearm ulnar nerve lacerations that were repaired, and the extent of recovery from the repair and the bridge graft remained unclear.[36,37]

To improve thumb pinch restoration, the opponens pollicis brevis branch was transferred to the terminal branch of the deep branch of the ulnar nerve. Thumb pinch improved in the 3 described cases.[38,39]

Discussion

There are limitations to this review that must be considered by the reader. As a scoping review, there is a possibility that some studies that reported specific NTs may have been missed. To mitigate this risk, we screened the reference list of each included article and searched several authors involved in research on NTs for more than 2 decades. We acknowledge that it is not possible to draw firm conclusions from the results of specific NTs of small cohort studies without a control group. This review solely aimed to provide an overview of NTs that have been attempted rather than comment on the efficacy of individual transfers or compare one transfer to another unless comparative data were available. When an NT without a reasonable result is reported, we were confident in recommending against its use.

Radial nerve

Isolated radial nerve injuries mostly occur after humeral shaft fractures or after iatrogenic injuries during fixations. Radial nerve injuries, if presented early could be primarily repaired if tension-free repair is possible; otherwise, these injuries require nerve grafting. Radial nerve repairs have a greater chance of satisfactory functional recovery because of the higher ratio of afferent to efferent fiber as compared to other upper limb mixed nerve trunks and generally short reinnervation distances to the critical motor targets from the common injury sites. However, graft repair outcomes remain unpredictable. If the patients present late, tendon transfers are historically the preferred choice, with predictable outcomes. Over the last decade, transfers from the median to radial nerves have gained popularity with promising preliminary results.[6]

The most prevalent transfer for wrist extension is the FDS, PT, or PQ to ECRB with MRC grade 3 and 4 outcomes (Figure 1). Bertelli et. al. showed that the PQ (AIN) to ECRB transfer had a greater

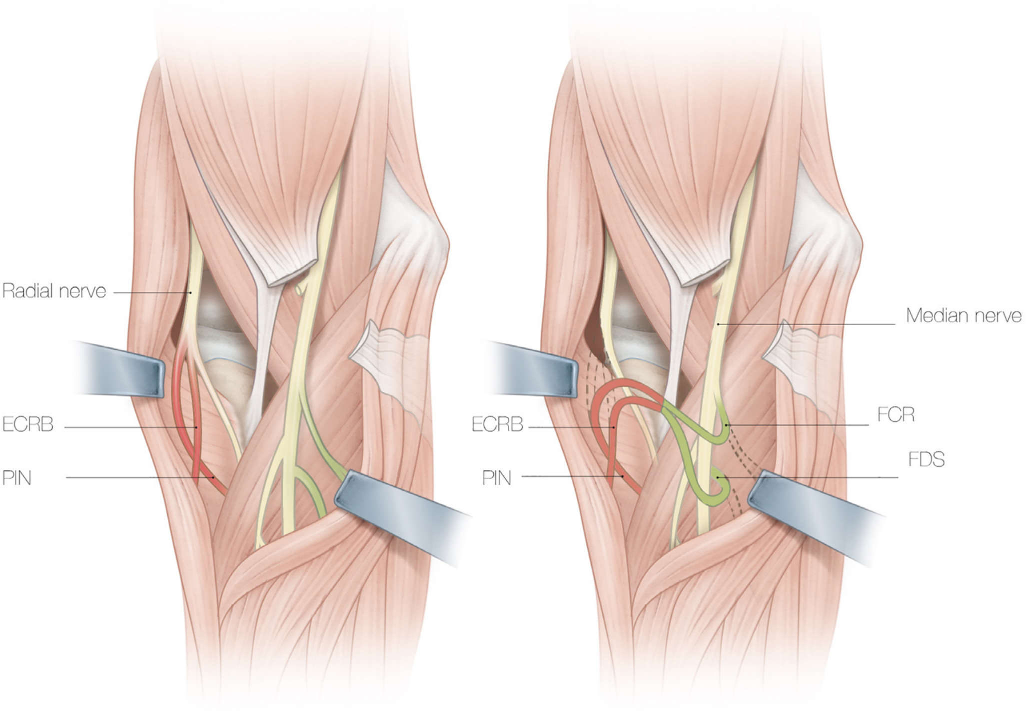

Figure 1. Nerve transfers for radial nerve palsy. Flexor carpi radialis (FCR) and flexor digitorum superficialis branch (FDS) (donor green) transfer to posterior interosseus nerve (PIN) and extensor carpi radialis brevis (ECRB) (recipient red).

range of motion, without radial deviation and better grasp strength than the traditional PT to ECRB tendon transfer.[14] Conversely, a recent study comparing tendon and NTs for wrist extension showed no significant difference.[15] Interestingly, Patterson et al. performed a hybrid tendon and NT, which was a PT to ECRB tendon transfer and FDS to ECRB NT, and this made comparison to other studies challenging. Moreover, two systematic reviews found no difference in wrist extension between tendon and NTs for radial nerve palsy.[40,41]

The most used reconstructive method for finger and thumb extension is FCR to PIN; however, it has less reliable outcomes than NTs for wrist extension. Ray et al. showed that 26% (5/19) of patients had a failure (<MRC grade 3) when performing this transfer for finger and thumb extension.[20] Additionally, Bertelli and Patterson showed in their comparative study that they had 14% and 36% failure rates, respectively, which is supported by others.[13-15,28] The challenging factor continues to be the indication, and in our opinion if the radial nerve is reconstructible and the nerve defect and graft are not more than 5 cm apart, then a primary radial nerve reconstruction should always be attempted. The classical and mainly used tendon transfer technique of PT to ECRB, FCR to EDC, and PL to EPL, remains a reliable alternative and in several cases a first-line treatment option. However, even with tendon transfers, there is a chance for failure, less range of movement at the wrist, less independent digital movement, and reliance on the tenodesis effect. When comparing NTs to tendon transfers, which are time-tested and reliable, one must consider that NT offers the possibility of restoring independent finger extension and simultaneous wrist extension. Furthermore, NTs are currently offered only at high-volume tertiary care centers, which may favorably bias outcomes. Despite this, NTs evidently require a longer recovery time with a risk of failure or a non-functional motor restoration.[40] In the absence of randomized comparative studies, we offer the patients the option of a nerve or tendon transfer, discuss the disadvantages of each technique including the option of a NT combined with a

PT to ECRB tendon transfer. The advantages of NTs must be carefully weighed against the possibility of an incomplete recovery requiring late salvage tendon transfer.

Median and anterior interosseus nerve injury

Historically high median nerve injuries were described as severe with absent pronation, reduced wrist flexion, and absent thumb, index and middle finger flexion and opposition. However, recently more thorough examinations have shown that functional motor deficits are not as debilitating as previously believed and can be missed when presenting in the emergency department.[17] The median nerve innervates the PT and quadratus and whilst tendon transfer restores pronation and may include the brachioradialis, biceps, supinator, or brachialis.[42] These tendon transfers are mostly used in obstetric brachial plexus palsy cases and are rarely used in adults with high median nerve injuries. Bertelli et. al. showed that in his cohort of 11 patients with high median nerve injury, pronation was preserved with MRC grade 4 power using brachioradialis and shoulder abduction for forearm pronation positioning. Therefore, an NT like the ECRB to restore PT is not a transfer that we would routinely use in our practice.[18]

Thumb opposition is also a function that may be readily reconstructed with FDS or EIP tendon transfers. However, thumb opposition positioning may be partially retained after high median nerve injuries.[17,18] Thumb opposition is compensated by the FPB, which has dual innervation from the ulnar nerve, and in at least 60% of cases, there might be a connection between the deep ulnar nerve and recurrent thenar branch (Riche–Cannieu connection). NTs for thenar reinnervation may be required selectively.

The most debilitating symptom after high median nerve injuries are paralysis of FPL and FDP of the index finger which can be restored with NTs to the AIN. The most used nerve donor is the ECRB NT to the AIN with most cases achieving MRC grade 4 (Figure 2).[21] Alternatives include the supinator nerve branches and brachialis NT to the AIN.[19,20] However, the brachialis NT has a longer reinnervation distance than the ECRB or supinator transfer and longitudinal dissection of the median nerve may be required to ensure that the correct recipient fascicle groups are targeted.

Ulnar nerve injury

Ulnar nerve injuries have a 71% lower chance of motor recovery when compared to the median nerve for similar injuries.[43,44] Prior to the advent of NTs, a high ulnar nerve injury could not be repaired to achieve useful recovery in intrinsic musculature in an adult.[45] The probably because the long reinnervation distance in a mixed nerve would result in an irreversible loss of muscle responsiveness to the incoming regenerating axons and associated muscle atrophy. The patient would experience a loss of dexterity, weakness of grip, sensory loss, and a noticeable aesthetic deformity.[46] Tendon transfers were historically used to treat these injuries, but they were physically limited by the principles of a singular, linear function and did not satisfactorily emulate the natural, intricate multi-faceted functionality of the intrinsics. With the knowledge that muscles had to be re-innervated within 12 months to prevent chronic denervation, NTs have gained popularity over the last 2 decades for the treatment of high ulnar nerve injuries by transferring expendable regenerating axons close to the target muscles.[4,47,48]

All articles in the literature, apart from one that was not included in this study, reported on high ulnar nerve injuries that were transfers for low median and ulnar nerve for amputations at the wrist level.[49] Low-level ulnar nerve injuries have good outcomes with repair or grafting and it is not conventional to perform NTs for these injuries. We aimed to study the efficacy and outcomes of NTs for ulnar nerve injuries, and the studies we reviewed included injuries from the proximal forearm or higher and were traumatic injuries, excluding compressive or inflammatory lesions. Most of the studies employed AIN transfer to the motor branch of the ulnar nerve (MUN), either alone or in combination with a sensory transfer (Figure 3). Other studies reported the use of a double end-to-side bridge graft from the median to ulnar nerve and pinch restoration with an opponens pollicis brevis branch to terminal division of deep branch of ulnar nerve transfer.[35,38,39]

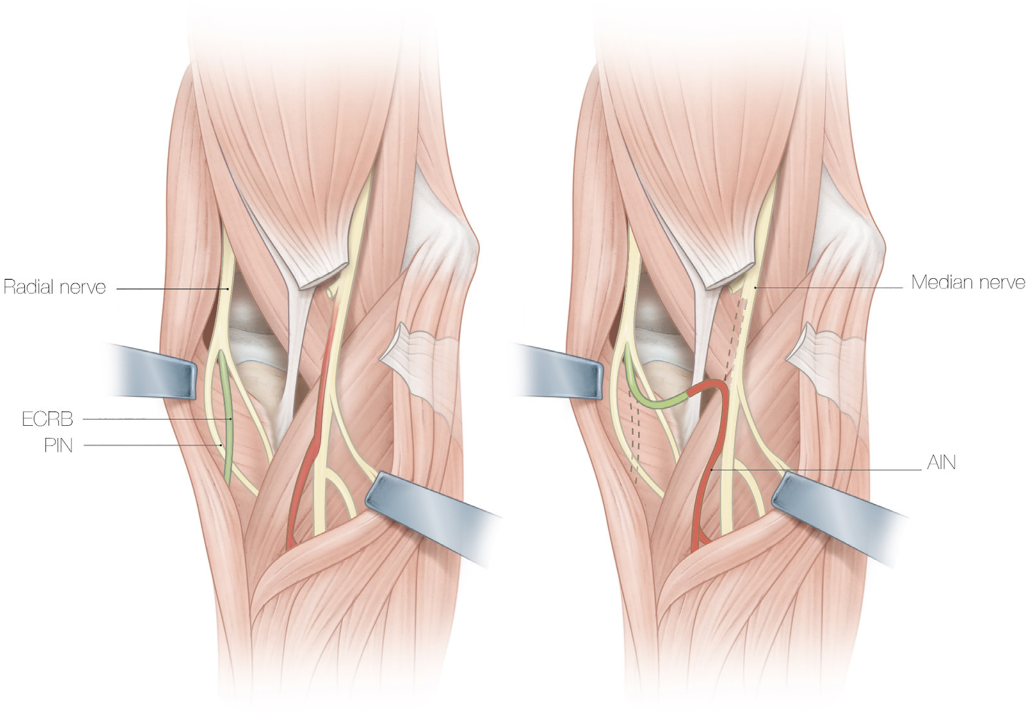

Figure 2. Nerve transfer for median nerve palsy. Extensor carpi radialis brevis branch (ECRB) (donor green) transfer to anterior interosseous nerve (AIN) (recipient red).

Regarding restoration of intrinsic function, Wang and Zhu first described using the PQ branch of the AIN to the motor branch of the ulnar nerve (MUN) as an end-to-end transfer to restore intrinsic hand function, in 1997, for amputation injuries at the wrist and were used for both median and ulnar nerve injuries.[49] Battiston used this technique specifically for high ulnar nerve injuries and combined it with a distal sensory transfer using the palmar cutaneous branch of the median nerve as well.[50] In rare instances, the PQ muscle could be absent or atrophic.[33] Surgeons should be aware of this possibility and acquire consent of the patient for the potential abandonment of the procedure or use a nerve graft to bridge the gap from the more proximal AIN. Moreover, it is not possible to differentiate this muscle from the PT on clinical examination but pre-operative electromyography is an option to ensure that the muscle is present, bearing in mind that this test is operator-dependent.[33] We believe this occurrence is too rare to justify using EMG on all patients preoperatively, especially as in the one case described by Dy et al, the patient did undergo a pre-operative EMG that did not detect this anomaly.[33] For the last 20 years, no other NTs or techniques have been described that reliably resulted in better outcomes in the context of a high ulnar nerve injury other than the AIN to MUN transfer; hence, this has been the mainstay of practice that has been adopted by numerous hand surgeons.

Nerve grafts or repair vs nerve transfers

When comparing distal NTs to nerve grafts, it appears that NTs would perform better, as grafts have two coaptation sites, use a sensory nerve donor to support motor axon growth, and usually involve a longer distance to the target muscle. Chan et al. observed at this in 1 patient who had an ulnar nerve reconstructed in the distal forearm with sural autografts and AIN transfer at the same point with no fascicular matching.[51] They found 90% of FDI function was from axons coming from the AIN transfer as opposed to the proximal ulnar nerve at 18 months and at 3 years, the AIN contributed

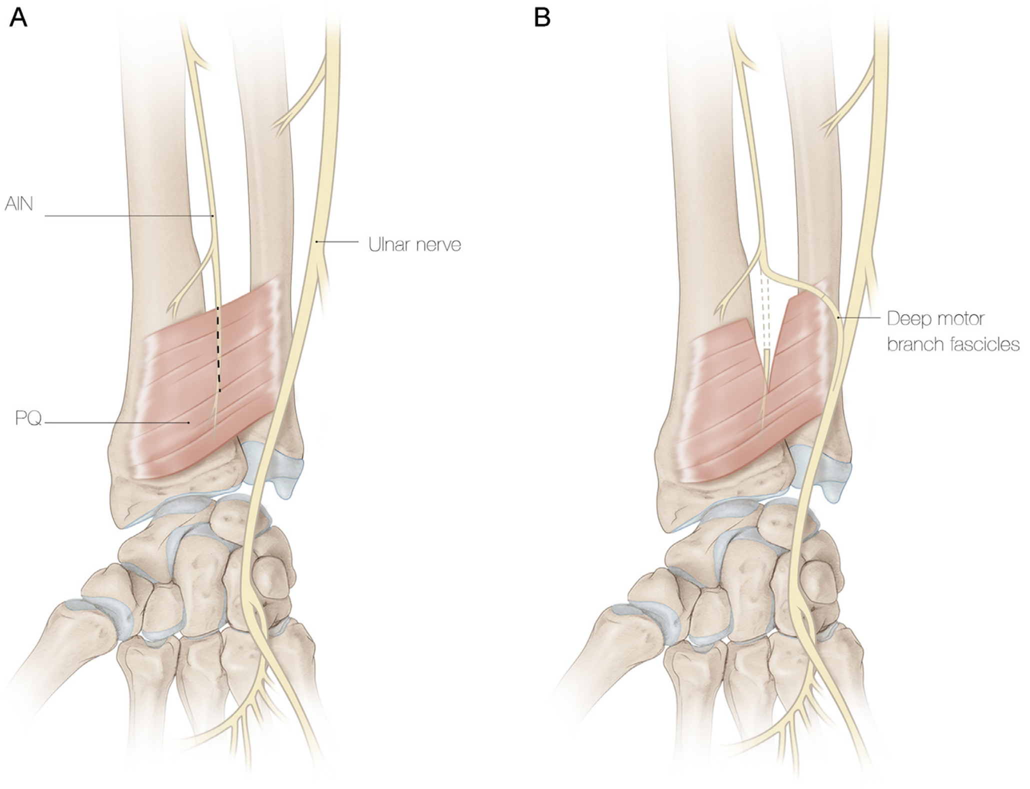

Figure 3. Nerve transfer for ulnar nerve palsy. Anterior interosseous nerve (AIN) transfer to the motor branch of ulnar nerve (MUN).

three times more axons than the ulnar nerve. The three studies that compared conventional methods of repair or grafting with NTs showed statistically significant better outcomes in the NT groups when compared to the conventional group.[9,27,28] In the study by Baltzer et al., even though the repair/grafting group underwent surgery at an average of 0.6 months after the injury when compared with the NT group who underwent surgeries at 5.9 months post-injury, the NT group still did better with 86% satisfactory outcomes compared to 14% in the repair group.[52] Flores demonstrated with statistical significance that 80% of patients that underwent NTs recovered hand grip power between 20–40 kg whereas only 5% of patients in the nerve grafting group could achieve that result.[27] Further research is needed to prove the efficacy of ETE neurorrhaphies, which is the most effective technique for this. In the interim, we recommend using conventional ETE NTs for Sunderland grade IV-V injuries in the proximal ulnar nerve. Although a clinical equipoise might exist regarding the treatment options for most nerve injuries owing to lack of evidence, we believe that high ulnar nerve injuries have sufficient evidence to warrant a distal NT, and units treating upper limb injuries should be aware of this to avoid unwarranted delay in treatment that could adversely affect outcome.

Post-operative regimens

NTs in the forearm can be performed without tension, and the adjacent joints can be put through their entire range of motion on table.[53] Depending on the site of neurorrhaphy, bulky dressings usually suffice for the first few days, and some surgeons would prefer using a splint to keep the wrist in neutral for 7-10 days, followed by gentle range of movement exercises to encourage nerve excursion and prevent subsequent scarring, adhesions, and neurostenalgia. A rehabilitation regimen should consider adjunctive procedures such as tendon transfers or volar plate advancements. Therefore, patients undergoing NTs should be fully assessed and evaluated by the hand therapist before and after surgery. The goals, while waiting for motor recovery, are to maintain supple joints and intact muscle function. Once reinnervation occurs, the goal shifts to motor re-education, in terms of recruitment of weak, newly innervated muscles, establishing new motor patterns, and cortical remapping.[28] Therapy should focus on recruitment of the donor nerves, especially in non-synergistic transfers such as the AIN to MUN. Thus, motor re-education needs to concentrate on recruitment of pronation which can be achieved with resisted pronation and simultaneous pinch exercises.[54,55]

There has been a paradigm shift in nerve injury treatment, with a recent international survey of 62 surgeons showing that 88% of the surgeons used NTs more frequently in the last 3 years.[47] Furthermore, we found small case series describing specific NTs, mostly without a control group. Future research should focus on comparing NTs to the natural history of motor recovery after primary nerve repair and tendon transfers.

Finally, normal function of the hand requires cutaneous sensation, proprioceptive control, and absence of pain. There is limited evidence, to date, to support the adoption of sensory NTs in the management of upper limb nerve injuries. There is a long reconstructive window for sensory recovery and a less compelling cause for the use of sensory NT rather than proximal nerve repair and grafts. The contribution of poor sensory recovery to hand functional impairments, even with an otherwise successful motor NT has not yet been explored.

In conclusion, early NT offers the potential for muscle reinnervation before the onset of critical muscle fiber degeneration and irreversible loss of muscle function. Knowledge of the available transfers and the expected outcomes can aid hand surgeons and patients in deciding the optimal treatment and expected recovery after NT. However, until there is a more robust evidence base, careful consideration is in order before offering NT to patients with PNI.

Conflicts of interest

The authors have no conflicts of interest to declare.

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Declaration of Generative AI and AI-assisted technologies in the writing process

None to declare.

Ethical Approval

Not required

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jpra.2024.01.005.

References

1. Padovano WM, Dengler J, Patterson MM, et al. Incidence of nerve injury after extremity trauma in the united states. *Hand (N Y)*. 2022;17:615–623.
2. Parylo J, Hodgson S, Chaudhry T. Tendon transfer versus nerve transfer for the reconstruction of key pinch and grip strength in isolated high traumatic injuries of the ulnar nerve: A systematic review. *J Hand Surg Asian Pac Vol*. 2023;28:327–335.
3. Gordon T. Peripheral nerve regeneration and muscle reinnervation. *Int J Mol Sci*. 2020:21.
4. Mackinnon SE. Donor distal, recipient proximal and other personal perspectives on nerve transfers. *Hand Clin*. 2016;32:141–151.
5. Tung TH, Mackinnon SE. Nerve transfers: Indications, techniques, and outcomes. *J Hand Surg Am*. 2010;35:332–341.
6. Brown JM, Mackinnon SE. Nerve transfers in the forearm and hand. *Hand Clin*. 2008;24:319 -v.
7. Mackinnon SE, Colbert SH. Nerve transfers in the hand and upper extremity surgery. *Tech Hand Up Extrem Surg*. 2008;12:20–33.
8. Rinker B. Nerve transfers in the upper extremity: A practical user's guide. *Ann Plast Surg*. 2015;74(Suppl 4):S222–S228.
9. Koriem E, El-Mahy MM, Atiyya AN, Diab RA. Comparison between supercharged ulnar nerve repair by anterior interosseous nerve transfer and isolated ulnar nerve repair in proximal ulnar nerve injuries. *J Hand Surg Am*. 2020;45:104–110.
10. Lurje AS. On the use of n. Musculocutaneous for neurotization of n. Radialis in cases of very large defects of the latter. *Ann Surg*. 1948;128:110–115.
11. Lowe JB, Tung TR, Mackinnon SE. New surgical option for radial nerve paralysis. *Plast Reconstr Surg*. 2002;110:836–843.
12. Mackinnon SE, Roque B, Tung TH. Median to radial nerve transfer for treatment of radial nerve palsy. Case report. *J Neurosurg*. 2007;107:666–671.
13. García-López A, Navarro R, Martinez F, Rojas A. Nerve transfers from branches to the flexor carpi radialis and pronator teres to reconstruct the radial nerve. *J Hand Surg Am*. 2014;39:50–56.
14. Bertelli JA. Nerve versus tendon transfer for radial nerve paralysis reconstruction. *J Hand Surg Am*. 2020;45:418–426.
15. Patterson JMM, Russo SA, El-Haj M, Novak CB, Mackinnon SE. Radial nerve palsy: Nerve transfer versus tendon transfer to restore function. *Hand (N Y)*. 2022;17:1082–1089.
16. Tian J, Leng M, Wang K, Huang Q. Pronator teres nerve branch transfer to the extensor carpi radialis brevis nerve branch for wrist extension reconstruction in proximal radial nerve injury following humeral shaft fractures. *BMC Musculoskelet Disord*. 2022;23:980.
17. Duraku LS, Schreuders TAR, Power DM, et al. High median nerve paralysis: Is the hand of benediction or preacher's hand a correct sign? *Plast Reconstr Surg Glob Open*. 2022;10:e4598.
18. Bertelli JA, Soldado F, Lehn VL, Ghizoni MF. Reappraisal of clinical deficits following high median nerve injuries. *J Hand Surg Am*. 2016;41:13–19.
19. Hsiao EC, Fox IK, Tung TH, Mackinnon SE. Motor nerve transfers to restore extrinsic median nerve function: Case report. *Hand (N Y)*. 2009;4:92–97.
20. Ray WZ, Yarbrough CK, Yee A, Mackinnon SE. Clinical outcomes following brachialis to anterior interosseous nerve transfers. *J Neurosurg*. 2012;117:604–609.
21. Bertelli JA. Transfer of the radial nerve branch to the extensor carpi radialis brevis to the anterior interosseous nerve to reconstruct thumb and finger flexion. *J Hand Surg Am*. 2015;40:323–328 e2.
22. Jensen EG. Restoration of opposition of the thumb. *Hand*. 1978;10:161–167.
23. Boswick Jr JA, Stromberg Jr WB. Isolated injury to the median nerve above the elbow. A review of thirteen cases. *J Bone Joint Surg Am*. 1967;49:653–658.
24. Schultz RJ, Aiache A. An operation to restore opposition of the thumb by nerve transfer. *Arch Surg*. 1972;105:777–779.
25. Bertelli JA, Soldado F, Rodrígues-Baeza A, Ghizoni MF. Transfer of the motor branch of the abductor digiti quinti for thenar muscle reinnervation in high median nerve injuries. *J Hand Surg Am*. 2018;43:8–15.
26. Mannerfelt L. Studies on the hand in ulnar nerve paralysis. A clinical-experimental investigation in normal and anomalous innervation. *Acta Orthop Scand*. 1966;Suppl 87(Supp. l):87 1+:.
27. Flores LP. Comparative study of nerve grafting versus distal nerve transfer for treatment of proximal injuries of the ulnar nerve. *J Reconstr Microsurg*. 2015;31:647–653.
28. Sallam AA, El-Deeb MS, Imam MA. Nerve transfer versus nerve graft for reconstruction of high ulnar nerve injuries. *J Hand Surg Am*. 2017;42:265–273.
29. Arami A, Bertelli JA. Effectiveness of distal nerve transfers for claw correction with proximal ulnar nerve lesions. *J Hand Surg Am*. 2021;46:478–484.
30. Chen SH, Mao SH, Lan CY, et al. End-to-side anterior interosseous nerve transfer: A valuable alternative for traumatic high ulnar nerve palsy. *Ann Plast Surg*. 2021;86:S102–S107.
31. Nyman E, Nyman T, Rubensson C, Thordstein M. Neuroplasticity following nerve transfer of the anterior interosseous nerve for proximal ulnar nerve injuries. *Plast Reconstr Surg Glob Open*. 2021;9:e3684.
32. George SC, Burahee AS, Sanders AD, Power DM. Outcomes of anterior interosseous nerve transfer to restore intrinsic muscle function after high ulnar nerve injury. *J Plast Reconstr Aesthet Surg*. 2022;75:703–710.
33. Dy CJ, Brogan DM, Colorado BS. Absence of the pronator quadratus muscle precluding distal nerve transfer. *J Hand Surg Am*. 2019;44:523 e1-5.
34. Pienaar C, Swan MC, De Jager W, Solomons M. Clinical experience with end-to-side nerve transfer. *J Hand Surg Br*. 2004;29:438–443.
35. Gesslbauer B, Furtmüller GJ, Schuhfried O, Roche AD, Sporer M, Aszmann OC. Nerve grafts bridging the thenar branch of the median nerve to the ulnar nerve to enhance nerve recovery: A report of three cases. *J Hand Surg Eur Vol*. 2017;42:281–285.
36. Magdi Sherif M, Amr AH. Intrinsic hand muscle reinnervation by median-ulnar end-to-side bridge nerve graft: Case report. *J Hand Surg Am*. 2010;35:446–450.
37. Isaacs J. Commentary on 'nerve grafts bridging the thenar branch of the median nerve to the ulnar nerve to enhance nerve recovery: A report of three cases. *J Hand Surg Eur Vol*. 2017;42:286–288.

38. Bertelli JA, Soldado F, Rodrígues-Baeza A, Ghizoni MF. Transferring the motor branch of the opponens pollicis to the terminal division of the deep branch of the ulnar nerve for pinch reconstruction. *J Hand Surg Am*. 2019;44:9–17.
39. Bertelli JA, Hill EJR, Arami A, Seltser A. Bilateral ulnar nerve injury in the wrist: Comparison of first webspace muscle reconstruction by opponens nerve transfer in the right hand versus direct ulnar nerve repair in the left hand. *Hand (N Y)*. 2023;18:NP5–NP9.
40. Compton J, Owens J, Day M, Caldwell L. Systematic review of tendon transfer versus nerve transfer for the restoration of wrist extension in isolated traumatic radial nerve palsy. *J Am Acad Orthop Surg Glob Res Rev*. 2018;2:e001.
41. Garg V, Regmi A, Negi NK, Yasam R, Sinha SK, Singh V. Distal nerve transfer to restore wrist and finger extension - A systematic review. *J Hand Surg Asian Pac Vol*. 2022;27:1000–1007.
42. Chuang DC, Ma HS, Borud LJ, Chen HC. Surgical strategy for improving forearm and hand function in late obstetric brachial plexus palsy. *Plast Reconstr Surg*. 2002;109:1934–1946.
43. Lan CY, Tien HY, Lin YT, Hsu CC, Lin CH, Chen SH. Prognosis of traumatic ulnar nerve injuries: A systematic review. *Ann Plast Surg*. 2019;82:S45–S52.
44. Ruijs AC, Jaquet JB, Kalmijn S, Giele H, Hovius SE. Median and ulnar nerve injuries: A meta-analysis of predictors of motor and sensory recovery after modern microsurgical nerve repair. *Plast Reconstr Surg*. 2005;116:484–494 discussion 95-6.
45. Gaul Jr JS. Intrinsic motor recovery–A long-term study of ulnar nerve repair. *J Hand Surg Am*. 1982;7:502–508.
46. Gottschalk HP, Bindra RR. Late reconstruction of ulnar nerve palsy. *Orthop Clin North Am*. 2012;43:495–507.
47. Mackinnon SE. Future perspectives in the management of nerve injuries. *J Reconstr Microsurg*. 2018;34:672–674.
48. Moore AM. Nerve transfers to restore upper extremity function: A paradigm shift. *Front Neurol*. 2014;5:40.
49. Wang Y, Zhu S. Transfer of a branch of the anterior interosseus nerve to the motor branch of the median nerve and ulnar nerve. *Chin Med J (Engl)*. 1997;110:216–219.
50. Battiston B, Lanzetta M. Reconstruction of high ulnar nerve lesions by distal double median to ulnar nerve transfer. *J Hand Surg Am*. 1999;24:1185–1191.
51. Chan KM, Olson JL, Morhart M, Lin T, Guilfoyle R. Outcomes of nerve transfer versus nerve graft in ulnar nerve laceration. *Can J Neurol Sci*. 2012;39:242–244.
52. Baltzer H, Woo A, Oh C, Moran SL. Comparison of ulnar intrinsic function following supercharge end-to-side anterior interosseous-to-ulnar motor nerve transfer: A matched cohort study of proximal ulnar nerve injury patients. *Plast Reconstr Surg*. 2016;138:1264–1272.
53. Moore AM, Novak CB. Advances in nerve transfer surgery. *J Hand Ther*. 2014;27:96–104 quiz 5.
54. Novak CB, Mackinnon SE. Distal anterior interosseous nerve transfer to the deep motor branch of the ulnar nerve for reconstruction of high ulnar nerve injuries. *J Reconstr Microsurg*. 2002;18:459–464.
55. Patterson JM. High ulnar nerve injuries: Nerve transfers to restore function. *Hand Clin*. 2016;32:219–226.